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SUMMARY REPORT

ON

WORK ORDER NO. 10,
TASK ORDER NO. TT

May 21, 1961

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SUMMARY REPORT

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INTRODUCTION

The Sponsor is interested in the potential development of a moisture condenser for use by individual untrained personnel in arid or desert areas of the world. This interest stems from a need to provide potable water for individual consumption in quantity and quality such as to enable a person to withstand the rigors of prolonged travel or of survival in such areas. It was our understanding that no suitable device or apparatus was (or is) available for this purpose, i.e., that no unit has been developed for use by an individual in obtaining from the air the quantity of water required to satisfy a human being's daily minimum requirements. On even the hottest and driest days, the air masses in desert areas reportedly represent a suitable source of water, providing, of course, that the water can be condensed and collected in a satisfactory manner.

Any equipment provided for this purpose should be small, lightweight, simple, and durable. A weight of 2.2 pounds and a size of about 6 x 6 x 12 inches were indicated as design goals in the consideration of an appropriate device.

Accordingly, an effort under Work Order No. 10, Task Order No. TT, was initiated, to investigate the practicability of developing a specialized moisture condenser of the type described herein. The proposed method of attack was to evolve ideas regarding devices which might serve the purpose; and to evaluate them, at least in preliminary fashion, from the viewpoint of possibly providing the basis for a subsequent development effort aimed toward achieving a unit which would embody the desired characteristics.

This report summarizes the results of the effort performed under Work Order No. 10, Task Order No. TT, during the period February 22 through May 21, 1961.

SUMMARY AND CONCLUSIONS

A number of methods have been considered for providing potable water to a desert traveler. None of those considered seems to be capable of meeting the weight and size goals as specified. Further, it presently seems doubtful that any system would be able to meet these goals, particularly the weight. However, if some increase in weight and size can be tolerated, the following three approaches appear to be very promising:

(1) The use of solid or liquid desiccants, with solar regeneration.

(2) A large, flat collector which would cool itself by radiating to the sky at night.

(3) A reciprocating compressor-expander with a rotating cylinder block, which would extract the water by centrifugal action immediately after it condensed in the expansion process.

Of these, the system with the smallest potential gross weight is probably the compressor-expander; it has been estimated that such a system would weigh about 8 pounds without a prime mover, and that an appropriate solar-energy-operated prime mover would weigh about 4 pounds. However, the exploitation of this method or of that based on the use of a desiccant would entail considerable developmental effort, as compared to the relatively small effort which would be needed to develop a suitable large, flat collector.

METHOD OF PROCEDURE

The problem presented for study was to consider methods of providing drinking water to a man traveling alone and on foot through the desert. It was specified that:

(a) The equipment should provide 2 quarts of water per day for 21 consecutive days.

(b) Any equipment provided should preferably weigh no more than 2.2 pounds and fit in a space about 6 x 6 x 12 inches.

(c) The equipment should be durable and easily operable by a man of average intelligence and mechanical skill.

In the absence of a definite environmental specification, it was assumed that the atmosphere contained 0.005 pound of water per pound of dry air, during the daytime and nighttime. Further, daytime temperatures were assumed to reach a peak of about 95 to 100 F, with long-period averages of about 90 F; nighttime temperatures were taken to be a constant 78 F.

The method of attack used for this program was to present the problem in general terms to selected members of our technical staff representing a variety of interests in the fields of chemistry, chemical engineering, physics, biosciences, and mechanical engineering. As a result, a number of approaches were suggested; these were subsequently screened to select those which seemed most promising in view of the specified requirements. The most promising ideas were then evaluated in some detail, in order to estimate how closely they would permit approaching the required performance and weight. Since the program did not provide for a thorough design study, evaluations were based on estimates of performance and weight that were detailed enough to permit only an approximate classification. For example, if a system depended on the use of a chemical, the required weight of the chemical was calculated and used as an indication of the minimum attainable weight of the system.

Table 1 summarizes the results of the study.

DISCUSSION OF RESULTS

The methods suggested for collecting water in the desert can be catalogued in five groups:

(1) Condensation of moisture from the air on a cold surface

(2) Absorption or adsorption of atmospheric moisture by suitable chemicals

(3) Extraction of moisture from the air by compression, cooling, and expansion

TABLE 1. PERTINENT METHODS OF COLLECTING WATER FROM SURROUNDINGS, PARTICULARLY FROM AMBIENT AIR

Method	Description	Estimated Minimum Weight	Remarks
1. Condensation on a cold surface	(a) Intermittent-absorption refrigeration system	Probably 50 to 60 pounds	-
	(b) Collector radiating to the sky at night	About 20 to 25 pounds	Probably not effective every night because of dependence on clear sky and negligible wind
2. Adsorption	Silica gel system with cyclic concentration and solar regeneration	28 pounds of desiccant, plus a fairly simple apparatus	Would require considerable developmental effort
3. Absorption	Liquid desiccants, such as lithium chloride solutions, with solar regeneration	4 pounds of desiccant, plus the required equipment	Would require some method of circulating desiccant to expose large surface area to the air during absorption; some desiccant might be lost by evaporation; would involve considerable developmental effort
4. Compression-expansion systems	Rotating-block compressor-expander with regenerative cooling of compressed air and centrifugal extraction of condensed water	About 8 pounds for compressor-expander, without prime mover; additional 4 pounds estimated for solar-energy-operated prime mover	Would require considerable developmental effort
5. Combustion processes	Combustion of hydrogen with condensation of water vapor produced	9 pounds of hydrogen, plus combustion and condensing equipment	Very bulky; difficult to handle

TABLE 1. (Continued)

Method	Description	Estimated Minimum Weight	Remarks
6. Miscellaneous methods	Extraction from soil or rocks, by solar distillation	Possibly about 5 pounds for soil; somewhat heavier for rocks	Depends on availability of the appropriate kind of soil or rock; there is no experience with such systems that could be used as a basis for estimating effectiveness

(4) Chemical reactions in which water is one of the products

(5) Miscellaneous methods.

These are discussed in some detail in the following.

Condensation on a Cold Surface

The collection of moisture from the desert air by using a cold exposed surface for condensation has some obvious limitations. With the assumed climatic conditions, the dew point of the air would be approximately 40 F; an appropriate cold surface would have to be appreciably below 40 F in order to collect much moisture. Below 32 F, the moisture would collect as ice, tending to insulate the collector from the air and to reduce the rate of collection. The low moisture content of the air would require the use of large collecting surfaces or a long collecting period in order to provide the required quantity of water. The use of a conventional compression refrigeration system would necessitate equipment of considerable weight, including a prime mover to drive the compressor.

The applicability of an intermittent-absorption refrigeration system, which would operate from solar energy, was analyzed. Units of this basic type were sold commercially many years ago as residential refrigerators which required no electricity. Basically, this type of system consists of two interconnected containers; one holds a solution of a refrigerant in an absorbent, which could be ammonia and water, for example, and the other is empty. To start the cycle, the container which holds the solution is heated. The heating drives off part of the refrigerant, which passes to the second container and condenses. When a suitable quantity of refrigerant is thus transferred to the second container and condensed, the heat source is removed. The first container then cools, the pressure in the system drops, and the refrigerant begins to evaporate from the second container; as evaporation occurs, the refrigerant passes to the first container and is absorbed. When the evaporation is completed, the cycle can be repeated. While the refrigerant is evaporating, it is extracting heat from its surroundings, and thus produces the refrigerating effect.

This system as applied to the problem of interest would be inherently simple, since it would operate from solar energy and would require only two basic parts, each of which would serve a dual purpose, plus an accessory. One part would act as the generator and the absorber, and the other as the condenser and evaporator. In addition, a solar-energy collector would be needed to provide a concentrated heat source for the generator.

A partial analysis of the intermittent-absorption system showed that the evaporation time required to collect 4 pounds of water would be inversely proportional to the evaporator area and would be a function of the air velocity over the evaporator surface. Even with the assumption of an air velocity of 20 feet/second, which would require a blower and a source of energy for the blower, an evaporator operating time of 4 hours would require an evaporator area of 25 square feet. Additional time would be required for the other phases of the cycle, and some difficulty might be caused by the necessity for removing the heat of condensation and the heat of absorption. In view of the limitations apparent in the evaporator portion of the system, no further analysis of this system was undertaken.

A simple method of obtaining water by condensation would use a large collector which would radiate to the sky at night. On a night, the sky has a low effective temperature. Assuming an effective sky temperature of about -80 F* at night, a perfect radiator with an area of about 100 square feet could collect about 4 pounds of water during the night. With a thin plastic film as the radiator, two other parallel films to shield the collector from ground radiation, and a lightweight, aluminum, tubular supporting structure, the entire assembly would probably weigh 20 to 25 pounds.

The successful operation of this type of collector would depend on having a clear, calm night. Cloud cover would make it inoperable; and wind would tend to raise the temperature of the device above the dew point, unless suitable shielding could be provided, and thus would result in ineffective operation. It is anticipated that a relatively small amount of developmental effort would be necessary in order to exploit this method.

Absorption or Adsorption by Desiccants

Many desiccants, both solid and liquid, are available that will absorb or adsorb moisture from desert air; in fact, there are solid adsorbents which will remove nearly all of the moisture. To be useful for the application of obtaining potable water, however, some means must be devised to ultimately extract the moisture from the desiccant as liquid. Desiccants are normally regenerated by heating to a high temperature, usually in the range of

*On a clear night, a radiating body located on the surface of the earth loses heat at a rate which would prevail if the body were radiating to an infinite sink at a temperature of about -80 F.

300 to 1000 F, depending on the desiccant. In the application of interest, the moisture would thereby be driven off as vapor and would have to be condensed. Also, while it would be possible to obtain the usual regeneration temperatures by concentrating solar energy, to attempt to provide for this function in a small portable unit does not appear practical.

However, there have been developed in Germany several thermodynamic cyclic processes utilizing desiccants which have removed water from the desert air, on the basis of a smaller temperature difference. In fact, units have been operated successfully on the basis of the temperature difference existing between a plane solar receiver and an adjacent shaded zone. In these systems, water plus water vapor was the working fluid, with dry air as the inert carrier gas. The Dannies' systems are outlined in the following; a detailed description is available in a series of three articles by J. H. Dannies that appear in the January, 1959, issue of "Solar Energy".

In the course of the Work Order No. 10 activity, calculations were made on these types of systems, to determine the weight of desiccant required to obtain 2 quarts of water per 24-hour day. While this value would not represent the total weight of the unit required, the other components could probably be made quite light in weight, particularly if a solid desiccant were used; the desiccant weight would therefore be a large part of the total weight and could be used as a basis for comparison.

Both solid and liquid absorbents were considered as desiccants in the calculations; a survey of solid-desiccant properties were made. Silica gel appeared to be by far the best for the present application and was the only solid for which calculations were made. This was the desiccant used by Dannies in his operating units, although he stated that other solids, as well as liquids, would function under the temperature conditions associated with the use of incident solar radiation. Liquid absorbents with the most desirable properties appeared to be lithium chloride and calcium chloride solutions, and both were used in the calculations.

Both the simultaneous and successive systems of Dannies were investigated analytically. However, the Dannies' simultaneous system was modified slightly to suit the requirements of the application of interest. For Dannies' application, self-operation and immobility were quite desirable; in his simultaneous system, which operated only during the daytime, two beds of desiccant were used, one facing east and one facing west. In the morning, the east desiccant was regenerated while the west desiccant was adsorbing moisture; in the afternoon, the functions were reversed. This procedure is rather inefficient for two reasons. First, the maximum solar radiation, which occurs near noon time, is not used, since the system is reversing at that time. Second, for most desiccants, 6 or more hours are not required for the equilibrium moisture content to be achieved. Therefore, on the assumption that a limited amount of manual operation would be possible in the application of interest, a shorter cycle was devised during which the beds would be alternately directed toward the sun. In order to determine the optimum time for the cycle, an analysis was made of the dynamic data on silica gel. While considerable extrapolation of the data was necessary to fit the conditions of interest, it was found that a 2-hour half-cycle would permit the regeneration of approximately 80 per cent of the adsorbed moisture. Beyond 80 per cent, the rate of regeneration would decrease rather rapidly, so a longer half-cycle appeared uneconomical on a weight basis.

The successive system explored by calculation was essentially that outlined by Dannies. This system involved adsorption in the cooler night air, followed by regeneration by solar energy and condensation in a closed system during the daytime.

Table 2 shows the results of the calculations. Most of the headings have already been explained or are self-explanatory. The temperatures for the simultaneous system were taken directly from actual data given by Dannies. For the successive system, the limiting adsorption temperatures simply represent the nighttime conditions; the typical spring and summer nighttime desert conditions are also actual data from Dannies for the Sahara Desert. The limiting regeneration dry-bulb temperature is the maximum air temperature in the closed system as obtained by solar heating during daytime operation, and the limiting regeneration dew point represents the shade-cooled condenser temperature. As the table indicates, the efficiency of the system is largely dependent on these regeneration temperatures. Most of the data presented in the table are only approximations. Ultimately, the actual values would have to be determined by testing a complete unit. However, they could be approximated more closely than is the case in Table 2, by a detailed heat balance using known heat-transfer correlations, once the actual physical arrangement of a unit was determined.

The systems based on using liquid desiccants appear quite attractive when only the weight of desiccant is considered. However, a word of caution

TABLE 2. CALCULATED DATA ON EXTRACTION OF WATER FROM DESERT AIR USING DESICCANTS (DANNIES' SYSTEMS), TO YIELD 2 QUARTS PER DAY

Type of System	Limiting Regeneration Conditions		Limiting Adsorption Conditions		Regeneration Efficiency, per cent	Desiccant Used	Cycle Efficiency, Water Yield / Water Adsorbed, per cent	Cycle Time, hr	Weight of Desiccant + Adsorbed Water, lb		Weight of Dry Desiccant, lb
	$t_{Dry\ Bulb}$, F	$t_{Dew\ P}$, F	$t_{Dry\ Bulb}$, F	$t_{Dew\ P}$, F					Max	Min	
Simultaneous - solid desiccant	117	47	94	94	80(1)	Silica gel	12	4(3/day)	59.5		47.6
Successive - solid desiccant	150	90	60 (Typical of spring nighttime in desert)	40	100	Silica gel	55	24	32.1	27.9	24.5
Successive - solid desiccant	150	90	74 (Typical of summer night-time in desert)	51	100	Silica gel	35	24	67.8	63.6	55.6
Simultaneous - liquid desiccant	117	47	94	85	80(1)	LiCl	12	4(3/day)	10.8		3.6
Simultaneous - liquid desiccant	117	47	94	85	80(1)	$CaCl_2$	12	4(3/day)	14		5.2
Successive - liquid desiccant	150	90	60	40	100	LiCl	44	24	12.9	8.7	3.5
Successive - liquid desiccant	150	90	84	51	100	LiCl	29	24	21.7	17.5	7.0
Successive - liquid desiccant	180	95	84	51	100	LiCl	78	24	8.0	3.8	2.6

(1) Depends on cycle time; this is an assumed value with some experimental basis.

must be injected in this regard, because the actual physical arrangement of either type of system when using a liquid desiccant has not been worked out completely. The calculations assume that such arrangements can be made to operate. The prospects of a practical, functioning unit based on either type of system appear promising, but considerable development work would be necessary.

On the other hand, physical arrangements of both types of systems when using solid desiccants have been designed and operated successfully. These units would probably be simpler than those required for liquid desiccants, but the weight of the required amount of solid desiccant would be much greater.

Compression-Expansion Systems

Systems in which a gas is compressed, cooled, and then expanded with work extraction are used for cooling gases in commercial liquefaction processes. The direct application of this technique to the desert-water-supply problem is not attractive, primarily because of the difficulty of cooling the working gas after compression. However, a system has been suggested that might be practical. This involves a compressor-expander with a rotating cylinder block, and regenerative cooling of the compressed air before it enters the expander. The key to this possibly applicable system is that the water would condense during the expansion process and be thrown clear by the centrifugal force created by the rotation of the cylinder block, before the air was reheated by passing through the regenerator. Such a machine would require a prime mover to supply the operating power; the prime mover might be a solar-energy-operated engine or possibly a man. The energy needed to produce the required quantity of water has been estimated to be about 2 horsepower hours; this would probably be too much energy to be provided by an average man.

It is estimated that the weight of an appropriate compressor-expander unit would be about 8 pounds, exclusive of the energy source. An air-cycle engine, operating from solar energy, might weigh about 3 or 4 pounds.

This system appears attractive in concept. However, both the compressor-expander and the prime mover would require appreciable development effort.

Chemical Reactions

Water can be produced as a product of a number of chemical reactions. Common examples of such reactions are those underlying combustion processes. In theory at least, one could burn materials which yield large quantities of water and collect the water from the combustion gases. Many hydrides yield appreciable quantities of water. For example, the combustion of 27.6 pounds of boron hydride (B_2H_6) will yield 54 pounds of water, or 1.96 pounds of water per pound of boron hydride. Similarly, the combustion of methane (CH_4) will yield 2.25 pounds of water per pound of methane. An even more direct approach would be to burn pure hydrogen, which will yield 9 pounds of water per pound of hydrogen burned.

Some additional weight would be required in connection with all of these processes, in order to provide equipment for combustion and for recovery of the water vapor from the products of combustion. Moreover, storage of gaseous fuels would be difficult. Storing under high pressure would reduce the volume, but would of course require heavy containers. A suggestion has been made that the hydrogen be stored at low pressure in balloons. This arrangement offers the unique advantage that it would impose no carrying load on the man.

However, it has some obvious problems in terms of volume, ease of handling, and susceptibility to observation in hostile territory. For these various reasons, none of the systems involving combustion appears promising.

Miscellaneous Methods

In addition to atmospheric air, rocks or soils represent a source of water which might possibly be tapped. Many kinds of rocks contain trapped water in amounts ranging from a trace to more than 10 per cent by weight. In concept, a solar still or a simple solar furnace could be used to drive off and collect the moisture from crushed rocks. This approach has been suggested by North American Aviation as a possible means of obtaining water from the rocks on the moon. Probably the equipment could be made reasonably light in weight so as to be portable. However, the applicability of this technique is dependent upon the availability of suitable rocks.

Soils extract moisture from the air and hold it in quantities which depend on the humidity of the atmosphere, and the particle size and absorption characteristics of the soil. The upper limit of the particle size of soils which will absorb or adsorb water vapor from the air is about 0.001 millimeter, corresponding to the particle size of a clay soil. Sand particles are much larger than this, and would hold practically no moisture*. The value of this source of water would depend on the availability of fine-particle soils. Again, extraction could probably be accomplished by a solar still. However, considerable effort would be needed to develop the required equipment and techniques.

*Puri, A. G., "Soils: Their Physics and Chemistry", Reinhold Publishing Co., 1949.

FUTURE WORK

No further effort in connection with the provision of potable water to a desert traveler is contemplated at this time. The three above-outlined methods which are considered to be quite promising have been discussed with the Sponsor. It is recommended that the Sponsor give further consideration to these. If the original specification of particularly the weight and also the size desired for the unit of interest could be relaxed slightly, we believe that a developmental effort to exploit any one of these methods would be likely to provide a satisfactory unit for this application.

Ask ... T/C E. Carculment, E&E

Thermodynamic Treatment of Air by Solar Radiation

By J. H. Dannies

Bonn, Germany

Rise in temperature of matter by direct solar radiation is relatively small for conventional technical utilization, if solar furnaces or solar mirrors are not additionally employed. Additional solar machinery is expensive and reduces thermodynamic efficiency by additional heat losses as well as financial attractiveness by additional amortization costs. Exploitation of small differences in temperature for transforming solar radiation into air conditioning and into refrigeration at economic running costs has not yet been developed. The known thermodynamic reversible cycles are not economical, and other methods have to be evolved.

A new reversible cyclic process for treating mixtures at atmospheric pressure with little rise in temperature has been set up, and its utilization for solar air conditioning and solar refrigeration is shown. It establishes procedures that are thermodynamically perfect and technically simple. Removal of drinking water from the air by solar pumping, solar refrigeration, and solar air conditioning are obtained without any intermediary machinery.

The new reversible cycle completes for humid air the principle of reversibility for exchange of heat or of matter either by utilizing differences in temperature more perfectly than has been possible up to now, or by lowering the obtainable refrigeration temperature at the expense of the cooling effect. Exchange of heat and of matter are no longer different means to the same end. In joint action they can now be employed for solving opposite problems and thus complement each other.

All changes of state in air conditioning and refrigeration within the considered range of temperature are performed in open atmosphere. In practice they are approximately reversible and do not demand mechanical or electrical work. The new reversible cycle extends exchanges of state and matter of humid air from the curve of saturation to the range of superheated steam. The cyclic procedure for solar refrigeration requires only water as a refrigerant and no other hygroscopic substance or pressure except atmospheric, and for drive small differences in temperature suffice.

INTRODUCTION

All origin of our being arrives from the sun. Like all other suns of the universe it is an accumulation of mass and energy, and like all other suns it acts radioactively in reducing the existing level of energy. It lavishes its mass, and the characteristic of the procedure is a permanent increase of entropy. Just as water flows asunder, so energy and, consequently, mass strive for the value zero at infinitely large entropy.

There are physicists who suggest entropy may be an oscillation. Then we have caught with "entropy" a lappet of a certain law of nature, the rest of which is unknown to us. If so, entropy would be a function of time, and ages later it would have the opposite tendency and decrease until the amplitude of oscillation has been passed again. Then entropy would once again start to increase; and a new edition of "our universe" would have to follow "our universe" with all its physical limits at all four boundaries because of Einstein's hypothesis, and eternity would be present in physics.

However, philosophy in natural sciences does not lead away from the initiator of all our actions and reactions—increasing entropy. Philosophy tries only to explain by mankind's conscious actions and reactions to increasing entropy, every development by its rules. Fortunately for our opinion of destiny, nature is patient and does not seem to count time as we do. For it permits braking of flux of energy to zero by accumulating energy quantities in wood, coal, oil, etc. It always acts elastically and postpones the striving of entropy to infinity wherever reasonably attempted. All living beings have found existence on this elasticity, but the strive to infinity can only be braked and never stopped. All our conscious and unconscious actions and reactions are directly and indirectly based upon this order.

Since mankind started to act logically, interpolation of procedures into the flow of entropy to infinitely large size has been tried. With mental perspiration, experience interpolating into the flux of energy has been brought into an order recognizable to us. By this order mankind is sometimes led to procedures which are economic in relation to flux of entropy. In thermodynamics these procedures are called "reversible cycles"—a precise term that rules as well as criticizes. Every procedure not harmonizing with reversibility is to be refused as it does not fit physically into our destiny—flux of entropy to infinity.

Branches of physics of unarranged masses, like thermodynamics, especially need reversibility as a criterion of physical efficiency. Up until now very few reversible cyclic procedures have been found for handling solar energy accumulated on the way to infinitely large entropy. These stored quantities are of another kind and another quality than energy delivered by direct solar radiation. For this reason success will most probably not be permanent for solar plants that combine direct solar radiation with conventional machinery which runs at a reversible cycle defined to accumulated solar energy.

The conventional way of engineering thinking in thermodynamics is application of high temperatures for moving small energy quantities. The method has always proved to be correct if, into flow to infinity of entropy, reversible thermodynamical cycles for the use of accumulated solar energy are interpolated. Accumulated solar energy and direct solar energy differ widely. Direct solar energy presents energy quantities in abundance, but they can be received only at low temperatures if complicated and expensive solar apparatuses are not interposed. For this reason, modes of treatment of energy other than the customary ones must be found before thermic and economic efficiency is proved.

This need can be met, and methods of utilizing direct solar radiation are already known which solve technical problems and attain remarkable efficiency. They employ reversible cycles, which have been unknown up to now and have been born out of the novel situation in which the abundant solar energy quantities are received at low temperature level. For instance, solar radiation is transformed into electricity directly by photovoltaic converters. They gain 11 per cent and more of the incident solar radiation in the form of electric energy.[2] The percentage is of an order that provides technical and perhaps already financial economy.

A search for a reversible cycle harmonizing with direct solar refrigeration and direct solar air conditioning has also been reported during the past years.[3] The reported tests indicate that already arrangements of absorption refrigeration procedures besides conventional ones are possible, and relatively low boiler temperatures have been used. Thus, the production of drinking water by solar radiation from brine of the consistency of sea water is accomplished by boiling by solar regeneration, followed by condensation within inert gas. The procedure used is in effect the same diffusion pattern employed for the latest absorption and resorption refrigerators. However, all these tests describe methods for the saturated and not for the unsaturated state of the employed mixture. Keeping to the saturation curve of pure humid air means a limitation in thought, and available possibilities are not recognized. The desired reversible cyclic process will not be found along but beside the saturation curve of humid air. Work on another aspect of refrigeration thermodynamics produced years ago the necessary reversible cycle; it belongs to the thermodynamics of mixtures.

Thermodynamics of mixtures is a relatively young branch of knowledge. It had not been advanced sufficiently for giving a summary survey[4] before 1937, though the reversible cyclic process in question was recognized in 1928. Intense practical work on it started in 1930.[5] It was presented publicly[6] for the first time in 1936, and it was discovered in developing absorption kryotherms* and resorption kryotherms.[7]† Since the advantages to solar techniques are obvious[3] it seems advisable to discuss the new reversible cycle in connection with solar plants in detail.

REVERSIBLE CYCLIC PROCESS WITH HUMID AIR AND ABSORBENT

Customary refrigeration processes do not suggest direct use of solar radiation. All depend upon utilization of solar energy stocked in one or the other natural energy accumulators. Most of them even require transformation of this stocked energy into mechanical work for producing the required effect. Usually, complicated arrangements are necessary, and permanent service of machinery is unavoidable. Such requirements do not suggest searching this conventional body of ideas for an existing solution of the unconventional problem of using direct solar energy for treatment of air in refrigeration processes.

However, roots for application of direct solar radiation exist already. Many difficulties are eliminated if mechanical work is not needed. Mechanical work is already considerably reduced in employing absorption refrigeration instead of compression refrigeration, and mechanical work is entirely cut out if absorption kryotherms are used. They reduce the drive for the refrigeration plant to the supply of heat produced either by combustion or electric resistance. The same principle of procedure would hold if direct solar radiation could be used for driving the plant, and if the system could be run with the refrigerant water, as water is one of the elements of life and cuts out all of the dangers of customary refrigerators. Furthermore, water is cheap and present everywhere. Atmospheric air carries water vapor, and all water vapor rising after evaporation

* Absorption and resorption refrigeration machines without moving parts, without mechanical pumps, without valves, and with additional inert gas are also an invention of E. Altenkirch. He and his collaborators called this type of refrigerator "kryotherm". Therefore, this term is also used in this paper.

† The National Physical Laboratory of Israel has recognized the importance of the new reversible cycle. Large-scale tests have been started to coordinate this type of refrigeration with climatic conditions at the site.

would not have to be collected for pedantically separated condensation but could be exhausted at any place.

Kryotherms make use of: (1) internal heat exchange without requirement of mechanical work; and (2) internal exchange of matter also without performance of mechanical work; and one may also presuppose (3) that the evaporated refrigerant quantity is moved by differences in temperature in utilizing certain geometrical configurations of the kryotherm. Solar radiation causes less rise in temperature than is necessary for known kryotherms; therefore, all movement of the evaporated water would have to be caused by smaller differences in temperature than the boiling heat that the customary kryotherm delivers. These three presuppositions have to be scrutinized for the suggested drive of kryotherms by direct solar heat and for the employment of water as the refrigerant.

By internal heat exchange different stages of technical procedures are often connected. Thus the heat exchanger between concentrated and dilute solutions of an absorption refrigeration machine may exchange a large quantity of absorption heat and often contributes decisively to the economy of the procedure.

Internal heat exchange usually excludes external work. The acting quantity of matter is led along one side of a surface to a high temperature and then returns along the other side to a low one or vice versa. The mathematical limitation is exchange of very large heat quantities while at the place of reversing the direction of flux of matter very small heat quantities are required for maintenance of the procedure. There are no difficulties in the use of any size of heat exchanger in any machinery. They work without motion and do not require any mechanical work while the substances exchanging heat pass, thus fulfilling the first presupposition.

Similarly, internal exchange of matter can connect different stages of a procedure. For example, humid air can be dried by diffusion through steam-permeable walls. Along them an air current is passed in counter current, going to a room of very high dryness and then returning. The procedure is used for ventilating rooms to be kept at negligibly small humidity. With this internal steam exchange, rooms are ventilated, and noxious gases are removed at the same time. The procedure shows that internal exchange of matter is possible without moving machinery.

At all these interchanges in temperature and/or composition, one quantity of substance moves first in one and then in the reversed direction. Such working cycles are obviously reversible. For instance, cooling air by volatilization of water until the dew-point is attained is made possible if heat exchange is arranged between the dry air which runs to the surface of volatilization and the humid air which leaves this surface.

The first and the second presuppositions are then fulfilled. The third one raises difficulties, as the use of water for refrigerant in mixture with the inert gas, "dry air," does not seem to be of sufficient elasticity. Up to now the mixture has been known to be controllably variable only in humidity contents along the saturation curve. Within the zone below this curve, water vapor contents of humid air have not yet been controllably varied. Thermodynamically the difficulties can be comprehended into two requirements:

(1) Independence of the saturation curve of pure water is to be obtained in exchanging humidity contents of air.

(2) Between humid air and absorbent the state of equilibrium has to be found for exchanging water vapor quantities.

The key to the problem is offered by hygroscopic substances. The vapor pressures at the surface of these absorbents supply the wanted solution, and hygroscopic matter is available in abundance.

Simply placing absorbent into an air conditioner or refrigerator does not yet gain reversibility. All procedures with hygroscopic matter for drying or humidifying air known up to now do not even approach reversibility. Careful separation of hygroscopic substances that carry different loads of humidity and conscientious conduct of the procedure are necessary. Otherwise, satisfactory approximation to reversibility will not be obtained, and always entropy flux to infinity determines that the rate of approximation to reversibility decides thermodynamic and, consequently, financial economy of the procedure.

Connection of the principle of reversibility of exchange of matter to hygroscopic absorbent seems to be the most perfect means to lead reversibly to every desired procedure in refrigerating humid air by solar radiation. The connection permits running the reversible cyclic procedure under atmospheric pressure, and the three presuppositions dictate obviously a system of four components for the needed refrigeration mixture:

(1) First mixture with the components (a) inert gas, for maintaining atmospheric pressure, and (b) humidity in form of water vapor;

(2) Second mixture with the components (a) absorbent and (b) humidity, absorbed in the form of chemical composition or adsorbed in the form of liquid water.

By this enumeration an open kryotherm is already described working with four components, if dry air is considered to be the inert gas and water is used for refrigerant. This composition delivers a new refrigeration procedure, if solar radiation will suffice for a regeneration.

Direct solar radiation is received at relatively low temperatures. It thus limits choice of absorbent, which always requires certain temperatures for regeneration, depending upon physical as well as chemical qualities

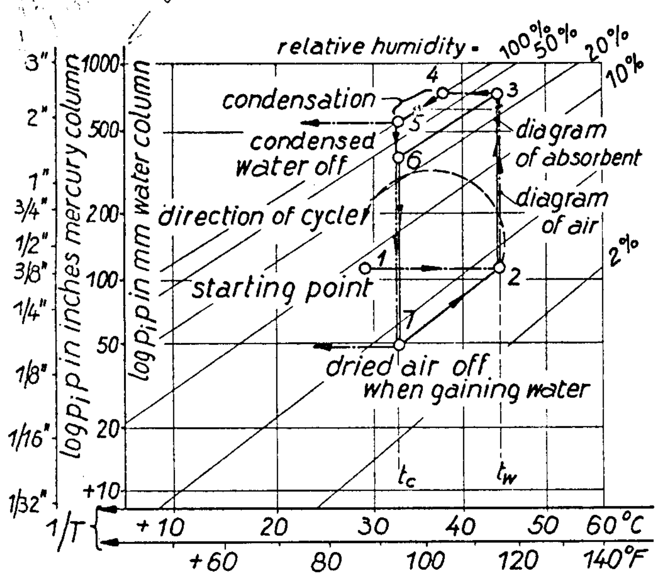

FIG. 1—Humidification of air—obtaining water from the air by solar pumping in arid zones.

but there remain quite a number of liquid as well as solid absorbents which comply with the temperature conditions of solar radiation. Suitable solid substances often work with phenomena of hysteresis in sorption; but these do not disturb performance, and solid substance is convenient to run a plant of commutating action, as plants driven by solar radiation have to be.

The thermodynamics of the procedure is somewhat complicated. At least three substances (inert gas, humidity, and absorbent) are involved; and, additionally, heat flux, which oscillates periodically with the commutating action, has to be considered. A method of presentation in a diagram is possible which permits considerable simplification in explaining thermodynamic associations. It reduces the explanation to a consideration of two variables: the pressure p and the absolute temperature T. The variables appear in the form of log p and of the reciprocal temperature $1/T$. With them, the diagram represents absorbents of constant water content by a straight line, and, if for inert gas dry air is used, the present water vapor pressure corresponds to the partial pressure of the humidity of air.

Humidification of air is shown in Fig. 1. It may be humidified at optional differences in temperature. The difference may be very small. In order to present actual values of a procedure, Fig. 1 and both the following figures present data of the mixture of silica gel with water.

Absorbent of different humidity loads and correspondingly different water vapor pressures p_2 and p_3 is situated within a warm range of temperature t_w—the regenerator. A corresponding quantity of absorbent is situated within a colder range of temperature t_c—the absorber; its partial pressure falls from p_6 to p_7.

If air from the free atmosphere of the state of starting point 1 enters, it is led to the regenerator and accepts the temperature t_w of the water vapor pressure p_2. It passes the regenerator, and its humidity is increased by vapor rising out of the absorbent in regeneration. At the end of regeneration the partial pressure rises up to p_3. With this vapor pressure the humid air is led into a cooled room, where it loses temperature. As soon as the temperature t_4 of point 4 is attained, condensation starts. Condensation is carried on until the lowest possible temperature t_c is obtained, and the gained water quantity is led off at point 5.

Then the air leaves for the absorbent in the cooled absorber. The air entering the absorber is still humid, as indicated by the partial pressure p_5. The absorber carries on drying and loads itself with humidity, until the dried air leaves it with the vapor pressure p_7. The difference in pressure $(p_2 - p_7)$ indicates the water quantity that has been retained in the condenser.

For this procedure the cycle may be run in the direction of the drawn arrows. Effective regeneration and absorption can also be arranged by reversing the flow of inert gas. The periods of producing water may coincide with solar periods; they may just as well conform to constructive or other regulations, and all degrees of liberty in disposition are maintained.

In the procedure the first water quantity enters the moving air in the regenerator. The second water quantity is absorbed out of air in the absorber, and the same quantity of water always changes place from absorbent in regeneration to absorbent in absorption. Then the difference in pressure $(p_4 - p_5)$ indicates in first approximation the water quantity that is gained by condensation. This water quantity has to be the same as that indicated by the difference in pressure $(p_2 - p_7)$. The water quantity changing place perpendicularly depends upon atmospheric conditions of the air to be treated, and it can rise to a considerable amount of the condensed water quantity. In first approximation the water quantity changing place is in direct proportion to the difference in partial pressure $(p_4 - p_2)$ respectively. $(p_5 - p_7)$ and the relation $(p_5 - p_7)/(p_2 - p_7)$ may be optionally large, and the difference in temperature $(t_w - t_c)$ for the impulse of the procedure may also be optionally small. Consequently, the first criterion of reversibility is fulfilled, and change of state not along the saturation curve but within the zone of superheated vapor is obtained.

Thermodynamically important is the discernment that the mixture of two components, inert gas and water vapor, must be treated by a second mixture of at least two components, if change of state is to leave the saturation curve. Practical arrangements of the cycle are simple, as it is usually found with fundamentally good procedures. Without external or internal mechanical work, liquid water is obtained out of even very dry air. The procedure may therefore be employed to dry rooms to a desired degree, if the air to be treated

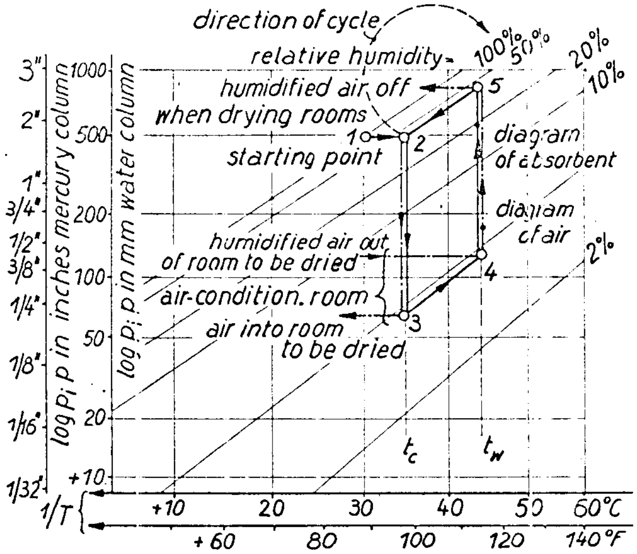

FIG. 2—Drying of air—solar air conditioning in humid zones.

enters the set from these rooms and not from the free atmosphere.

The procedure in Fig. 1 describes the left-way cycle. Reversibility requires proof of existence of the right-way cycle. It is given by the opposite task. This is drying of air by optionally small differences in temperature. The right-way cycle has been drawn in Fig. 2. The condenser of Fig. 1 is in Fig. 2 replaced by an "evaporator" between points 3 and 4. Now air of the free atmosphere, of the partial pressure $p_1 = p_2$, enters first the absorber of the cold temperature t_c. The entering humid air is dried by the absorbent until the partial pressure p_3 is obtained.

Then it may be led into a room either to be dried or to be cooled, and within, the partial pressure rises to p_4. It accepts the temperature t_w when, after leaving the room, it meets the absorbent regenerated by solar radiation. Here the moving air is reloaded with humidity re-arising out of absorbent until the partial pressure p_5 is obtained. With this humidity the air leaves for the free atmosphere.

In comparison to the water quantity received by the air in passing the "evaporator", the water quantities exchanged by absorption and regeneration at the small difference in temperature $(t_w - t_c)$ may again be optionally small. Again the water quantities correspond to the fraction in partial pressures $(p_2 - p_3)/(p_4 - p_3)$. Therefore, the right-way cycle also fulfills conditions of reversibility, and reversibility of the new cyclic process is proved.

Small differences in temperature have been intentionally presupposed in the description of the drive of the procedure. Unavoidably, the thermodynamic consequence is that a certain minimum quantity of heat must be exceeded for the drive of the cycle, and in economic consideration a cheap source of energy for the drive is necessary, i.e., infringement on entropy flux to infinity has to be paid for. Yet reversibility rewards by reducing the payment, and only a small rise in temperature is necessary for movement of air. As solar radiation is of long duration per day, relatively large quantities of absorbent become necessary, and absorbents of excellent qualification, as well as of low price, have been found and tested for running the procedure.

Assuming that the differences in temperature for the drive must be small would be a misapprehension. Their smallness has been chosen to demonstrate reversibility of solar plants. Wherever larger differences in temperature are available, they may be employed for the developed cycle. The larger the differences in temperature that can be produced for driving the plant the greater the economy in energy consumption.

If saving of artificial energy is required, the new reversible cycle can be utilized for heating as well as for refrigeration. For demonstration, Fig. 3 has been drawn. It shows the first step in obtaining temperatures lower than atmospheric ones. The procedures for solar refrigeration plants have been developed much further than Fig. 3 indicates; yet description of this first cooling step demonstrates refrigeration methods, as well as the connection of the cycle of Fig. 3 to that of Fig. 2.

Air enters the absorbent of drying action in the state of point 1 and is dismissed for the room to be refrigerated in the state of point 3. Additional drying and the reduction of the vapor pressure of point 3 still further is necessary for cooling, as the evaporation temperature depends on this pressure. This additional drying of the moving air may be done by absorbent which has been regenerated at higher temperature than t_w. In the same manner, drying by a substance of lower temperature than t_w is possible. The lower temperature may be obtained first by heat exchange between points 3 to 4 and points 6 to 7 and then by water or ice in

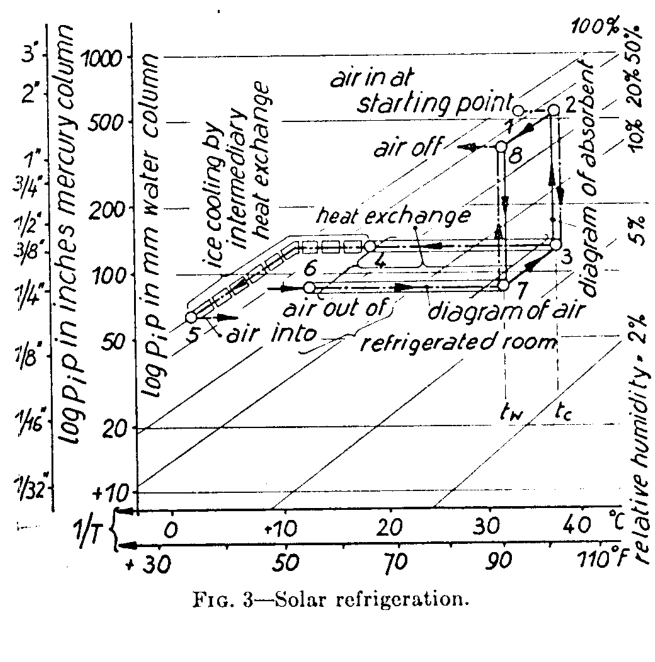

FIG. 3—Solar refrigeration.

intermediary heat exchange until point 5 has been attained. In this case the air current returning from the cooled room passes the absorbent in regeneration under conditions that may even cause $t_w < t_c$, as it has been drawn in Fig. 3. In regeneration, the partial pressure rises from p_7 to p_8.

This reversible cycle is entirely different from customary cooling of air by ice or by water in evaporative coolers, and the procedure is as far as possible remote from reversibility. It bars reversibility by change of state at constant enthalpy and—worse—at increase of entropy. Evaporative coolers do not pay attention to air being thermodynamically a mixture of two substances which at constant pressure can be reversibly treated only by a second mixture.

In the cyclic procedure of Fig. 3 a steam quantity is delivered by regeneration that corresponds to the difference in partial pressures $(p_8 - p_7)$ while at the place of changing the direction of flow a water quantity is removed that corresponds to the difference in partial pressures $(p_3 - p_7)$. Again $(t_c - t_w)$ may be small and again $(p_8 - p_7)$ may rise considerably above $(p_3 - p_7)$. The obtained increase in refrigeration must, therefore, correspond to the relation $(p_8 - p_7)/(p_3 - p_7)$. This increase obviously comes more into effect the warmer and the more humid the air to be treated. It presents the key for development of every refrigeration procedure of the new cycle.

Superiority of the new procedure to evaporative coolers is also proved by Fig. 3. The figure demonstrates that the new cycle has the same refrigeration effect with only $\frac{1}{3}$ to $\frac{1}{2}$ of their consumption of water or ice.

Nearly all these thermodynamic possibilities have been known. The new cyclic procedure offers for the first time their technical utilization because now every desired change of state can be run reversibly for treating air of unsaturated as well as saturated water vapor contents.

The methods are presented in the log $p - 1/T$ diagram. As simple as the practical plants are, diagrammatical simplification should not hide the intricacy of calculation of the procedures. With actual figures, troublesome methods of convergence become necessary, and only approximately correct results can be calculated. The temperatures of humidity contents of the absorbent are expressed in the diagram by isotherms, and these are the straight lines. Actually the temperatures follow curves which approach only the lower or the upper end of the drawn isotherms. The effective form of these curves, and with them the actual diagram, always depends mainly upon the quantity of inert air passing through the mass of absorbent.

REFERENCES

1. Löf, George O. G., "Cooling with solar energy." *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona, 1955*. p. 172.
2. Pearson, G. L., "Electricity from the sun." *Ibid.* p. 281–88.
3. Telkes, Maria, "Solar stills" *Ibid.* p. 73–79.
4. Bosniacovic, Fr., *Technische Thermodynamik*. Dresden und Leipzig, Theodor Steinkopf, 1937.
5. Altenkirch, E., *Mein Lebenslauf*. Karlsruhe, C. F. Müller Buchdruckerei GmbH, 1955, p. 22–23.
6. Altenkirch, E., "Neue thermodynamische Wege der Luftbehandlung." International Symposium of Refrigeration 1935; reports by the International Institute of Refrigeration, Paris. Vol. 3, p. 740–51. With this report the late E. Altenkirch presents to the public the fundamental idea of solar kryotherms upon which all development of solar refrigeration is based. "Treatment of air by solar radiation" proceeds from this idea to the comprehension of the elements for a description of practical consequences.
7. Dannies, J. H., "Die Resorptionskryotherme." *Allgemeine Wärmetechnik*, July 1956: 200.

Solar Water Pumping

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The left-way cyclic process, introduced in the preceding paper, is described for obtaining water out of air. Two working methods are utilized. The first one delivers drinking water out of air without any service, maintenance, etc. The second method requires opening a cover above the absorbent during the evening. The quantity of drinking water depends on climatic conditions at the site. In Central Europe, the water quantity obtained with the second procedure corresponds to 0.90 to 1.70 mm daily rainfall on a yearly average. In the North Sahara, about 150 to 200 miles off-coast, it is about 10 per cent more. Water delivery of the first procedure is less. The delivered quantity depends also upon climatic conditions at the site. More water is obtained in dry zones, but delivery will never be of the same quantity as given by the second method.

INTRODUCTION

The left-way cycle of the new kryotherm for humid air has been described in the preceding paper by explaining enforcement of condensation of humidity contents of atmospheric air. The cycle consists of absorption of humidity out of air and of regeneration in dismissing humidity into air. For regeneration, heat is to be introduced into the apparatus, and absorption requires discharge of heat. If solar radiation is used for regeneration heat, the part of the water pump receiving solar heat must be exposed to sunshine, and the absorber obviously requires shade. Both demands can be fulfilled simultaneously or successively. Both possibilities require different designs which shall be discussed.

For simultaneous resorption and absorption, motionless operation of the cyclic process is obtained simply by situating the first main axis of the solar water pump in a north-south direction and the second one perpendicular to the surface of earth. Then in forenoon the east part is regenerated by solar radiation, and the west part is situated in the shade and in absorbing action. In the afternoon both parts reverse their action because of the change of angle of incidence of solar radiation.

Successive regeneration and absorption of solar plants is obtained by using solar radiation during the daytime for regeneration and during the night-time without sunshine for absorption. The successive as well as the simultaneous procedure may operate in a cycle of one day, and then the working period of solar water pumps will coincide with the daily period of sunshine. This parallelism in time of period and of daily solar radiation is not compulsory. Duration of the working period in regeneration and absorption may last from one second to the whole day in order to correspond to any technical requirement.

More important than the time question are the dispositions for absorbent. If, for instance, for the period of one day:

(1) Two quantities of absorbent are arranged for simultaneous action, each time of absorption and regeneration will last about 6 hours. Absorption time of the first absorbent quantity is regeneration time of the second one, and vice versa.

(2) One quantity of absorbent is arranged, the times of absorption and regeneration have to follow each other in successive operation, and each time of work will last about 12 hours.

The water quantity obtained with the second procedure is greater than that with the first one. The cause is not this doubling of time; there is another reason. For the second procedure the solar water pump has to be situated with the first main axis in a north-south direction and with the second one exactly east-west. For the first procedure the first main axis has also to be situated in a north-south direction, but the second main axis has to be perpendicular to the surface of the earth for automatically reversing the east side regeneration into absorption and vice versa for the west side. Then the second procedure receives only a fraction of the solar driving energy. As the intensity of solar radiation follows in first approximation the sine curve, with maximum at 12 o'clock, a considerable portion of the energy collected for regeneration of the first procedure is lost. The solar drive can obviously be thus reduced to less than 50 per cent of the second procedure.

SIMULTANEOUS SOLAR WATER PUMPING

The technical scheme of a simultaneous solar water pump is given in Fig. 1. The sketch is to represent a cross-section. Both side walls are made of heat-permeable material. They have good thermal contact to the absorbent.

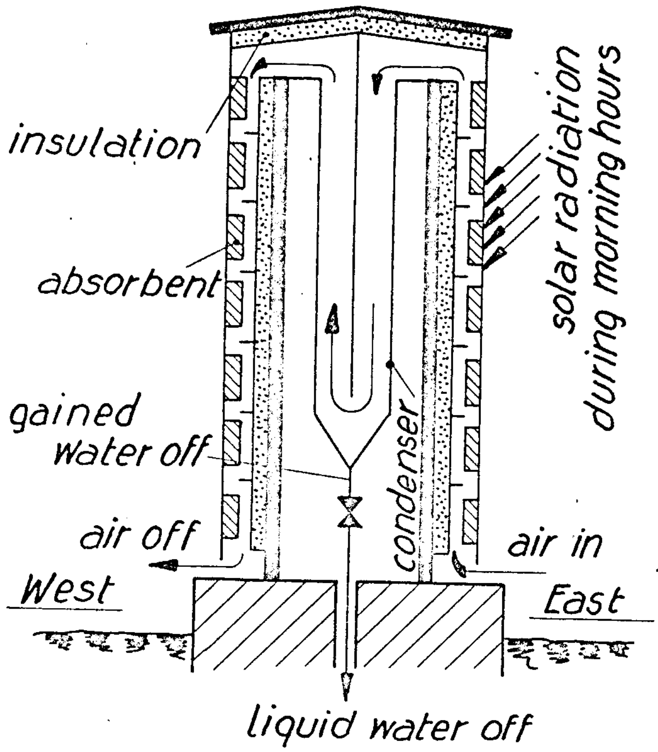

Fig. 1—Simultaneous solar water pump.

Heat received for regeneration has to be well retained within the compartment that contains the absorbent, as an air temperature as low as possible has to be maintained for condensation of steam. Insulation between both the external compartments and the condenser reduces the heat flux through their back. To prevent solar heat from entering the condenser and the absorbent compartment the ceiling has also to be insulated.

The condenser is made of material of small resistance to h... flux. The form has been drawn schematically in the same manner as the sketch for elucidation of technical action of the left-way cyclic process.

During forenoon solar radiation strikes the external east wall. The incident heat flows into the air contents and into the absorbent within the easterly air duct. By this heating the absorbent releases retained humidity in the form of steam. The steam enters the air volume within the easterly air duct and increases the relative humidity of this volume.

At the same time the entering heat raises the temperature of the air contents. Both influences diminish the specific gravity of the air. This air volume swims within atmospheric air and starts ascending. A kind of chimney draught comes into existence within the easterly air duct, and the air moves during forenoon in direction of the drawn arrows.

After leaving the duct the air enters the condenser. It is situated in the shade and of lower temperature than the air duct where the air enters. Therefore, the air is cooled in the condenser.

The considered air volume is pressed through the condenser by new warm air which arrives from the easterly air duct during forenoon for the same reason. The air volume leaving the condenser is then compelled to enter the air duct of the west wall, which contains unsaturated absorbent and where the moving air loses its humidity by absorption. The rising absorption heat leaves the westerly air duct through the westerly heat-permeable wall situated in the shade during forenoon.

Experience teaches that the main part of the humidity carried by the moving air current is absorbed by the upper part of absorbent. The following way through the lower part dries the moving air to a lower degree of humidity than it possessed when entering the apparatus. Granulation of absorbent depends upon this knowledge of the difference in absorption.

The absorbing part also implements the movement of air. Here buoyancy is lost by delivery of specifically light vapor to the absorbent, and specific gravity is further increased by cooling for absorption. Both influences draw the air from the regenerated part. The air volume between the easterly and the westerly parts is like a connecting ribbon, and permanent flux of air reentering the free atmosphere behind the absorber is maintained.

During the first forenoon water is not yet present in the condenser. Only a certain amount of humidity of the air passing the solar water pump is retained. This humidity quantity does not suffice to saturate the absorbent completely, and the absorbent must be saturated before any water quantity is delivered. This saturation by air takes some time.

During the afternoon solar radiation heats the west wall, and the same procedure is repeated. The temperature of the air and absorbent rises by solar heat entering the westside air duct, and now the east wall remains cool. Water vapor pressure within the westerly absorbent rises correspondingly, and it expels vapor. This vapor quantity causes a rise in humidity contents of the air within the westerly duct. By it and the rise in temperature the air starts moving, but now in reverse to the direction of the forenoon.

The vapor entering the solar water pump together with the dry air is, during the afternoon, of about the same quantity as during forenoon; but the vapor quantity, moving within the solar water pump from the westerly to the easterly air duct, is now greater, because the moving air current receives additionally the vapor quantity which has been absorbed by the absorbent of the westerly side during forenoon and which now is driven out of the absorbent again by solar radiation. The present vapor pressure is now obviously higher than during morning hours. During afternoon, therefore, more moisture is offered to the absorbent of the ea... than has left it during forenoon.

However, the air leaves the easterly air duct drier than it entered the westerly one because the easterly quantities of absorbent which are down-situated have also been heated during forenoon. By this regeneration they have been dried and are now of strong absorbing action.

Each air quantity thus percolating the solar water pump leaves water within. The retained quantities of humidity increase the water contents of the absorbent until at last a humidity quantity of certain weight starts an oscillating movement of vapor between both the masses of absorbent. In the condenser, then, a relative humidity of 100 per cent is always maintained while the temperature of moving air sinks and humidity must fall out. Then an "artificial rain" is started between both the masses of absorbent and delivers the required liquid.

One hundred per cent relative humidity remains for the air that leaves the condenser and always delivers water to the absorbent of the shaded side to such an extent that after each change of direction of solar radiation a new quantity of humidity is supplied to the circulating air for maintaining saturation. By this artificial atmosphere of 100 per cent within the internal room of the solar water pump, delivery of water becomes entirely independent of humidity conditions in the free atmosphere.

The absolute humidity contents of the air quantity passing the pump are almost entirely retained by the down-situated absorbent, and they are the gained water quantities. Their weight varies with the humidity conditions at the site. Likewise the intensity of solar radiation at the site influences performance, and the delivered water quantities are a function of the climatic conditions. In dry tropic and subtropic zones the simultaneous solar water pump is of unique performance. For instance, in the Sahara, about 150 to 200 miles off-coast, drinking water has been gained at relative humidities of less than 5 per cent.

Up to now, large simultaneous solar water pumps have not been run in permanent installations. The principle of this kind of solar water pump has been proved by test plants. The largest type has been 22 sq ft on either side receiving solar radiation. This test plant was run in Central Europe, in South Italy, and in the Sahara. Practical experience with these test sets has shown that humidity can leave the unit again at the end of the half-day period, and then efficiency decreases if the quantity of acting absorbent is too small for the climatic conditions present. Similarly a decrease in efficiency is found if the moving air quantity becomes too large for the quantity of absorbent present.

The gained water quantity depends upon the absorbing capacity of the absorption material, its quantity, and upon the attained regeneration temperature. By throttling the moving air volume these dependencies can be influenced. The optimum of gained water quantity is obtained by regulating correctly the moving air volume. Every solar water pump has a certain ratio between moving air volume and present quantity of

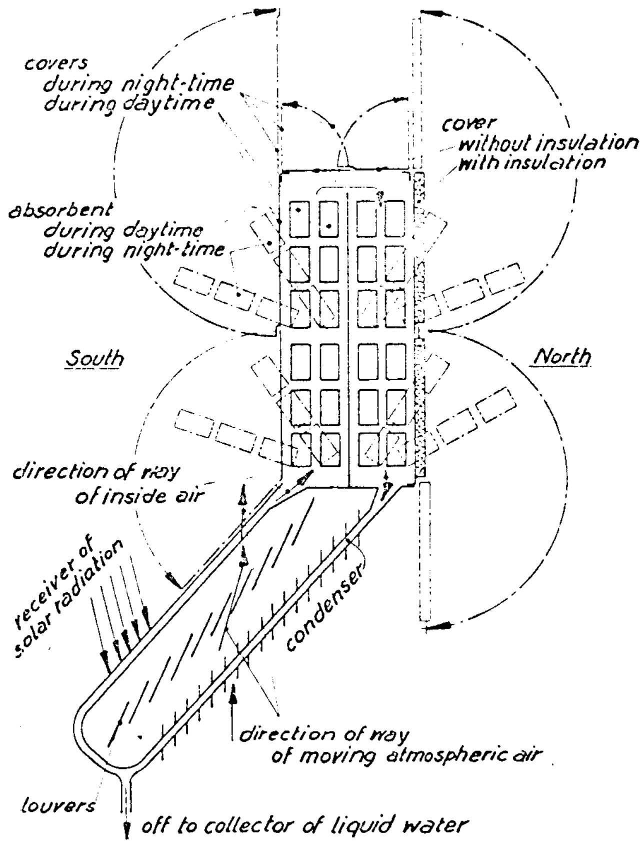

FIG. 2—Successive solar water pump.

absorbent which depends on climatic conditions at the site. It has to be regulated only once when starting. Then it runs without any service or maintenance.

SUCCESSIVE SOLAR WATER PUMPING

Solar water pumping by successive absorption and regeneration was assumed to take double the time of the simultaneous procedure. The period is to last 24 hours, and solar radiation for regeneration is to be utilized during the whole day. The receiver of solar radiation is situated north-south as shown in the technical scheme of Fig. 2. In the northern hemisphere the receiver will accept solar radiation arriving from the south, as the sketch demonstrates. In the southern hemisphere solar radiation arrives from the north, and the indications in the sketch of north and south have to be exchanged.

The receiver of solar radiation is the main part of the arrangement, as it keeps the pump running. The solar water pump has to be situated in such a way that the solar radiation is received not quite perpendicular, and movement of air is induced within the receiver. This is obtained by a somewhat oblique position of the receiver of solar radiation. Then all accessory parts can be situated for meeting technical or other requirements. One of these solutions has been sketched in Fig. 2.

The receiver is to be painted with a color that approaches absolute black; likewise, the side walls of the simultaneous solar water pump of Fig. 1 have to be colored. The material used for the receiver is of the same small thickness and of the same good thermal conductivity as that chosen for the external walls of the simultaneously working solar water pump.

Below the collector of solar radiation, louvers are to retain heat rays from the condensing surface. The air current caused by heat leaving the condenser is shown by arrows. They are to indicate the warmed air which rises from the condenser and then passes the receiver. To protect against loss of solar heat, this air is obviously better than air of the temperature of the surroundings. Still better is insulating the receiver at the underside, thus eliminating unwanted heat flux almost entirely.

The absorbent is packed into a compartment. The compartment of Fig. 2 shows movable covers. Upon the situation of this compartment, upon its covers, and upon their service all the various designs of the successive water pumps are based.

The compartment of the design of Fig. 2 is divided in the middle by a separating wall enforcing a certain airway. For regeneration, the best collection of arriving heat is necessary, and, therefore, the compartment is painted in dull black at all surfaces facing south. Both the side walls and the north wall are situated in the shade, and during the daytime are always at a lower temperature than air coming from the receiver of solar radiation. To minimize heat loss for increase of regeneration, the covers of the north wall and of the east and west side are insulated.

During daytime the absorbent is kept in a parallel position which enables movement of air at low resistance against flux. During night-time all covers are opened. The regenerated absorbent is brought into such a position that air can lave around all sides and easily deliver humidity for new absorption. The night-time position of absorbent and covers is shown in Fig. 2 by dotted lines.

The working method is just as simple as that of simultaneous solar water pumping; but there is a difference. While simultaneous solar water pumps work without service, successive solar water pumps require opening of covers above the absorbent and the absorbent has to be put into night-time position. During the night the temperature drops. The decrease of night temperature depends upon certain qualities of the environment. In dry tropical zones the differences between day and night are considerable. For instance,

TABLE I

	at 7 hours	at 13 hours	at 18 hours
Midwinter (January)	37.6°F; 71%	57.2°F; 41%	53.8°F; 41%
Spring (April)	59.5°F; 48%	75.7°F; 29%	75.4°F; 27%
Midsummer (July)	84.6°F; 32%	99.6°F; 23%	100.6°F; 20%
Autumn (October)	60.0°F; 58%	77.0°F; 35%	74.8°F; 34%

Colomb-Bechar, situated in the rain shade of the Atlas, about 500 miles south of Oran, has on the average the results shown in Table I. These figures are average values and the actual fluctuations are larger. Sometimes during night-time even the state of haze is approached in the driest zones.

The percentage presents the relative humidity, and the data show those known dry desert climates which have an absolute humidity of 20 to 55 grains vapor per lb dry air. This specific weight is not much less than the absolute humidity contents of Central European air. The humidity suffices adequately for solar water pumping of successive action, as tests in these desert climates have proved. It saturates the absorbent during night-time up to the state of equilibrium corresponding to the present humidity.

Before the sun rises the absorbent is put into dehydrating position and the covers are closed. No other service is required. Then solar radiation heats the air within the receiver. It becomes warm and loses specific gravity. It obviously starts rising out of the receiver in the direction of the drawn arrow and flows into the packets of absorbent.

The absorbent is heated by the arriving warm air. It releases vapor upon being regenerated and humidifies the entering air. The humidified air leaves for the condenser. This air is still considerably warmer than the air of the free atmosphere, and the vapor from the absorbent travels with the moving air. When passing the condenser the air is cooled, and humidity falls out by condensation. A better expression is perhaps "water thaws" out of the moving air.

When replacing part of the condensing surface by glass, one may see the formation of dew drops on the glass. The falling drops are collected. The same thing occurs in winter when the windows of a warm room become wet by condensation. Following all the proceedings visually in detail has generally proved to be the best method in evolving solar refrigeration from the theoretical range of ideas.

The water received is not gained in uniform quantities, nor does it depend only upon the daily fluctuation of solar radiation. Another effect influences and delays the performance. The warmed air arrives at the first volume of absorbent and regenerates it. The rising water vapor enters the moving air current, but it is not yet carried to the condenser. It is re-absorbed by absorbent between the place of beginning regeneration and the exit of air out of the absorber. Herewith the volume of absorbent is regenerated in the beginning, and the remaining volume of absorbent is additionally loaded with humidity. The delimiting surface between regenerated zone and loaded zone is thus gradually moved on, and the water quantity of the loaded zone becomes larger and larger. Then the state arrives that the quantity of absorbent not yet regenerated cannot receive any more humidity, and now the whole quantity of humidity raised by regeneration remains within the moving air current. The humidity load of the moving air becomes heavy, and during the last time of regeneration a really damp mass leaves the absorbent in regeneration to be condensed.

After being dehumidified to a degree depending on the atmospheric temperature around the condenser, the air is drawn out of the condenser and returned to the receiver. Here it is rewarmed and the cycle restarted. The procedure has been tested with a plant of practical size. The solar receiver was of a size of 22 sq ft. Larger permanent plants have not yet been run. The tests were run in Central Europe up to a latitude of about 52°, further in Southern Europe, and in the Sahara.

Three test plants of this size were always erected at about 1.5 to 2 miles distance and conjointly run. The net results can therefore be considered to be safe. There have been obtained:

Central Europe at 50 to 52°	
May–August	0.13 to 0.16 USA qt/sq ft/day
March–April and September–October	0.07 to 0.10 qt/sq ft/day
November–February	Even during this time drinking water is obtained here. Because of relatively small solar radiation at 51° to 52°N the gained water quantities are small.
Sahara, about 150 to 200 miles off-coast	
June–July (max.)	0.16 to 0.20 USA qt/sq ft/day
January (min.)	0.03 to 0.06 USA qt/sq ft/day

These water quantities from the air and not from a well are surprisingly large. They prove, for instance, that the roof of a building in dry zones will suffice for obtaining from the air more drinking water than the inhabitants require.

NOTE: Solar water pumping by absorption kryotherms is treated for the first time in public by this paper. For this reason, other literature cannot be enumerated.

Solar Air Conditioning and Solar Refrigeration

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Improvement of climatic conditions affects productivity and efficiency. Running of conventional air conditioners to produce climatic environment of greater productivity is a problem in arid and humid zones without adequate electricity supply, and unconventional means have to be employed. Application of solar radiation for drying or humidifying air for conditioning without intermediary machinery is one of these solutions for increasing productivity and efficiency. Solar air conditioning without intermediary machines is explained, and ways are described for practical execution of solar air conditioning.

Solar refrigeration without intermediary machinery is a continuation of solar air conditioning. Drops in temperature of 30°F and more are possible by it. Lower temperatures require employment of ventilators and heat exchangers. Their use provides temperatures of 33° to 35°F within a moving air current which is today's limit in solar refrigeration. This cooling of an air current permits at least cold storage of any size with temperatures of 40° to 50°F.

For lower temperatures, rational resorption is reviewed in regard to regeneration by collectors of solar heat. With the same solar heat quantity inserted for regeneration, rational resorption delivers 2.50 to 3.25 times more refrigeration performance than conventional absorption refrigeration.

INTRODUCTION

The direction to the right of the new cyclic process for treating air for air conditioning has been described in the first paper in this series. The new right-way cycle utilizes the reversed direction described in my second paper. While for producing water, humid air on the way from regenerator to absorber is important, for air conditioning, moving of dried air is necessary. The reversed cycle presents a reversed picture in performance; but action of absorption and solar regeneration remain as they have been in "solar water pumping."

All necessities in situating the absorbent for successive or simultaneous working remain, and the main axis of the air conditioner must again be placed in a north-south direction. This requirement is a restriction in disposition; but it is compensated for by running the air conditioner without need for artificially produced energy. For simultaneous action an inclination of 90° of the absorbent to the west-east axis is again necessary. Also successive procedure requires that again absorbent be almost flat to the surface of soil, and all the prescriptions of disposition of absorbent for solar water pumping are repeated.

Then the same effect of solar radiation is presented, and the obtained performance per unit of radiated surface is again smaller with the simultaneous procedure than it is with the successive method. In solar water pumping fully automatic service is given by simultaneous action. It is of more striking performance than the successive procedure because it cuts out any service, and, in a way, really squeezes water out of air with any humidity as if it were a sponge.

A similar striking performance is given by air conditioning or refrigeration using simultaneous absorption and regeneration. These air-conditioning plants also work without any service, and they again follow ad libitum any prescription in absorption or regeneration. Also, the time of the period which may last from one second to the whole day may follow technical or other requirements.

Successive absorption and regeneration is also of larger performance, as it again receives the larger quantity of solar radiation and again additional service is required for utilization of the induced drying capacity of absorbent. The successive and the simultaneous procedures will be discussed.

Generally it should be noted, for all solar plants following the new cyclic process, that:

(1) Serviceless procedure is presented by all arrangements standing perpendicularly to the surface of soil, with their main axis in north-south direction. These plants may work just as well alone as cooperating with a second standing unit.

(2) Always, service is required for running solar plants situated not perpendicularly to the surface of soil. The service is, in the end, always a mechanical movement of air or absorbent.

SIMULTANEOUS AIR CONDITIONING

Fig. 1 presents a sketch of the cross-section of a building air-conditioned by solar radiation. Neither the

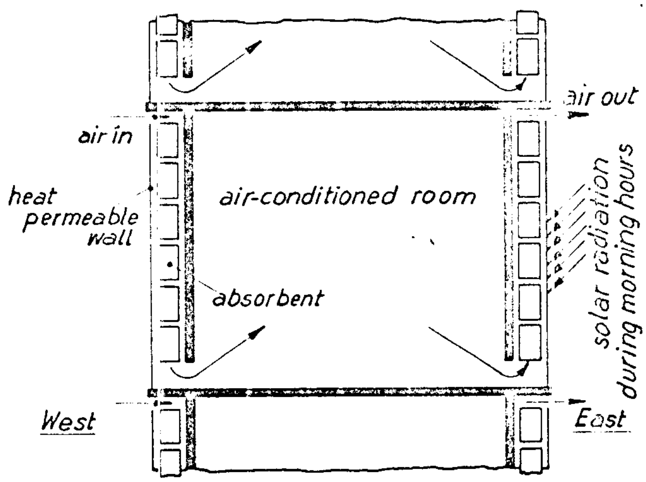

FIG. 1—Solar air-conditioning.

dimensions of the building nor of the absorbent are to scale. The cross-section has been drawn to explain working conditions distinctly. For actual air-conditioned rooms the relation between the dimensions of the absorbent and the dimensions of the building is very much smaller than the drawing shows. Furthermore, in the sketch both the walls contain nothing but absorbent. Absorbent of this quantity is not always necessary. The quantity depends on atmospheric conditions on site. Drying of air in humid tropics requires more absorbent than drying of air in hot tropics, and the weight of absorbent corresponds to the humidity quantity to be retained.

Both the external walls are of heat-permeable material. They may have good thermal contact to the absorbent, or they may only protect the absorbent against external atmospheric conditions without direct contact, as Fig. 1 shows. The arrangement depends entirely upon the thermodynamic and mechanical qualities of the employed absorbent.

The external walls are to be painted with a dull color of emission capacity approaching absolute black. Since during absorption heat is to be transmitted to atmospheric air from air passing the inside of the external wall, this should also be painted in a dull color, especially if the absorbent is not in direct contact with this wall.

Collected solar radiation appears in the air duct in the form of heat. This heat is to remain for regeneration, and the walls between the air ducts and air conditioned room are to be of adequate insulating capacity. Usually brick walls of customary thickness suffice. Thermal conductivity of concrete is two to three times as large as that of bricks. Furthermore, concrete walls are of higher strength than brick walls and always of smaller thickness. To retain the trapped solar energy for regeneration they have to be insulated.

Both the air ducts which are shown in Fig. 1 of "Solar Water Pumping" have to be employed for solar air conditioning as well. Instead of the condenser of this sketch, the room to be air conditioned has now been situated in the stream of air; but the direction of air movement is reversed, and the humidity contents of the air differ in comparison to the previous figure. There, absolute humidity contents decrease between entrance and exit of the condenser, while now they increase, i.e., the reversed cycle is in action.

To obtain the correct dimensions of the air ducts, many tests have been run. The results of all these tests yield dimensions for the absorbent and the air duct which warrant very good performance at best efficiency.

Different materials for the external wall and many kinds of absorbent have been checked in commercial plants running in temperate climates. Also, in dry and humid tropics as well as in subtropics, many materials have been tested. The tests have been run with small units of the individual detail to be checked, and the dimensions of the units were all of sufficient size to allow technical judgment. From net results, one may expect in the tropics at least the same performance as obtained in temperate climates.

During forenoon, solar radiation falls on the external east wall. The heat enters the eastside air duct and warms the air contents and absorbent on this side. The absorbent is regenerated by warming and loses water vapor, which enters the air volume of the air duct. The warmed mixture of dry air and vapor is obviously of smaller specific gravity than the outside atmospheric air. The air within the air duct swims within the volume of atmospheric air, and having become lighter than the surroundings it starts rising. Ascension of air within the air duct leads it out of the uppermost opening.

This air volume must be replaced. It is substituted by air entering from the room to be air conditioned through the opening in the east wall. The air-conditioned room has only one other opening, the opening in the low part of the west wall, and air can leave the air-conditioned room for the easterly air duct if it is replaced by air entering after having passed the absorbent in the westerly air duct.

The westerly quantity of absorbent has been regenerated the afternoon before. Therefore, it dries passing air, and the air volume entering the room to be air conditioned has attained that state of dryness which compressor air conditioners produce by cooling along the saturation curve.

The entering air reduces the relative humidity of the air-conditioned room. This relative humidity can be regulated by very simple means. The effect of the described air conditioning depends mainly upon the relation between weight of absorbent and weight of moving air. Throttling of the moved air volume suffices for regulation, as more relative humidity is extracted out of the moving air and vice versa. In humid tropics, for instance, the relative humidity can easily be regulated within a range of 20 per cent up to 75 per cent by these means, and the drying capacity of the plant depends upon trapped solar radiation for regeneration.

Regeneration is very similar to that described for solar water pumping. Heating by solar radiation starts regeneration at the lowest layer of absorbent. The vapor rising out of it is partly re-absorbed by higher situated absorbent, and a surface of delimitation between regenerated and unregenerated absorbent ascends. Difference in water contents of the absorbent is the more distinctly marked the higher the surface of delimitation has risen. In the end again, a really hazy air leaves the regenerator from about 10:30 until 11:30 in the forenoon and from 3:30 until 4:30 in the afternoon.

When the moving air has to extract only a small weight of humidity out of the air-conditioned room, it is less loaded when entering the regenerating section and the obtained effect in regeneration is then greater. The drying capacity is preserved for cases of fluctuation in load. In correctly designed solar air conditioners, preservation occurs frequently.

Such reserves are more than adequate for rainy days with only a few sunny hours. Tests have shown that a period of 7 to 10 days without sunshine at all can pass before the drying capacity of regenerated absorbent has disappeared totally. As periods of permanent overcast sky of this duration do not usually exist, air conditioning is maintained during rainy seasons. This elasticity has been proved in Central Europe, even at 52°N, by solar air conditioners during cloudy and foggy November–December. During this time solar air conditioning maintains here a humidity of 35 to 45 per cent, and the performance of solar air conditioning remains sufficient for adequately drying wooden planks for manufacturing.

Water possesses one of the largest heats of evaporation, and customary air conditioners that work with compressor refrigerators always require large refrigeration performance in relation to accomplished air conditioning—if designed correctly. Large performance of compressor refrigerators requires large power consumption, and the height of electricity bills of compressor air conditioners is well known.

Even this power is usually smaller than technically necessary because, for reasons of sale, with all compressor air conditioners reduction in initial price and running costs is accomplished by reducing the size of the required refrigerator. Then cooled but not sufficiently dried air has to remove combustion heat of the human body, and unavoidably "draughty air" results, well-known in compressor air-conditioned cinemas, etc.

Sensitivity of the human body is not increased when the temperature rises. In subtropics and in tropics of more than 70° to 75°F, the human body does not require any other conditions to relieve combustion heat than in temperate climates; but it is more exposed to climatic fluctuations because of thin and light clothing. It then acts sensitively to small alterations in temperature, and temperature shocks with all their consequences for health cannot be avoided when a room of lower temperature than the usual surroundings is entered, as, for instance, a compressor air-conditioned banking office.

Of entirely different action is the described method. In the air-conditioned room permanent conservation of at least atmospheric temperature is warranted. The source of "flue by air conditioning" is cut out because not the temperature but the relative humidity is shifted to obtain air-conditioning effect.

To get rid of combustion heat, the human body produces more perspiration the higher the surrounding temperature. If the relative humidity of air is high, even at "warm" temperatures, liquid perspiration remains upon the skin, because humid air cannot sufficiently absorb the additional water. If the relative humidity is small, perspiration does not appear upon the skin. It is immediately evaporated from the pores and taken up by dry air. Evaporation or sublimation is not possible without latent heat, and this heat must be delivered from somewhere.

It is delivered by the human body, and evaporating perspiration cools the human body in surroundings of warm temperature but low relative humidity. In humid tropics of 85°F a relative humidity of about 20 to 50 per cent corresponds roughly to our customary climates of about 65° to 70°F. Practical solar air conditioning, therefore, will regulate the relative humidity in tropics to 50 per cent and more and not to 20 per cent or less. These figures are fundamental, and they are touched only secondarily by temperatures of surrounding walls, velocity of air, etc.

The matter of the surroundings we live in is full of absorptive substances. Furniture, clothes made of hair or cotton, etc., are absorbents. Even bricks and concrete walls are of certain absorptive capacity. Therefore, air conditioning during daytime provides accumulation of drying capacity in every room, and air conditioning during night-time is always adequately accomplished.

Demonstration of this solar air conditioning by accumulation is presented by storing flour, salt, or sugar in humid tropics. Test storing of these materials in Liberia has shown that in solar air-conditioned rooms, flour can be safely stored unpacked and does not get mouldy. Unpacked salt and sugar do not start dissolving and do not swim away in solar stores; they remain crisp. Automatic air conditioning by solar radiation does not require any service. It runs automatically and is of the more intensive action the more intensive the solar radiation. It brings the relief in human life longed for in all humid tropics and subtropics for infirmaries, stores, offices, living rooms, sleeping rooms, etc., at the same time avoiding complicated machinery.

SUCCESSIVE AIR CONDITIONING

The same influencing of climates is possible by using successive solar air conditioning. Just as in the case of solar water pumping, the absorbent has to be situated almost flat to the surface of soil. This position takes care of utilizing the incident solar radiation during the whole day, and it catches more solar heat than the arrangement of simultaneous procedure. More weight of absorbent can be regenerated or regeneration is of more intensive effect than the simultaneous position delivers.

The period of absorption can be shortened by moving the absorbent, and mechanical drive for movement of absorbent becomes necessary. Without movement of absorbent the period of the procedure may last 24 hours; that means 12 hours regeneration and another 12 hours absorption; then movement of air during the night is required. All solutions of the problem of successive air conditioning necessitate the use of energy for the movement of one element. Energy consumption of this drive is always small. However, it is the first step in employing intermediary machinery for solar absorption.

The utilization of a ventilator for movement of air, for instance, does not affect the simplicity of the procedure. For sleeping rooms in humid tropics a fan is a customary appliance. Its power consumption will suffice to air-condition the sleeping room all night. The absorbent has been regenerated during the daytime, and movement of air along absorbent then has been induced as described for simultaneous air conditioning. During night-time the fan starts working, leads the air along regenerated absorbent, and dry air is introduced into the sleeping room all night. This drying is rather intensive. It permits the recreative sleep which is needed in humid tropics.

The recreative effect may be increased still further by additional refrigeration as described in the following section. Then sleep in humid tropics will begin at the temperature of the surrounding air but at a reduced and comfortable humidity. By morning, the temperature has slowly cooled down to Central Europe climates, and refreshment by effectual air conditioning is assured with the additional ventilator.

SOLAR REFRIGERATION WITHOUT INTERMEDIARY MACHINERY

Solar air conditioning can be easily compared to solar refrigeration. Refrigeration is obtained by evaporation of water within the current of dried air, and refrigeration machinery consists of this one evaporator. No other implements are needed and no compressor or metallic regenerator, electric or other drive, condenser, pipes, etc., are necessary.

In Fig. 2 the west corner of the room of Fig. 1 has been redrawn. Solar radiation during morning hours falls on the east wall. A tray with water is placed below

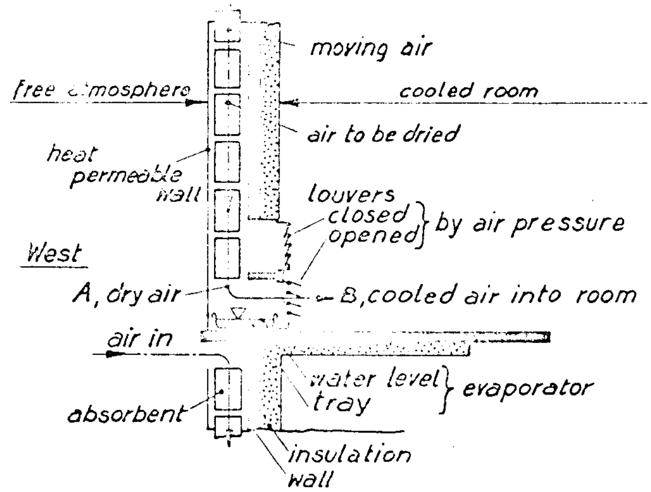

FIG. 2—Solar refrigeration without intermediary machinery.

the absorbent. Water is a refrigerant like any other, and this water quantity is the refrigerant of solar refrigeration. The dried air leaving the absorbent passes over the water surface. Rise in temperature of air, connected to drying by absorption, has been almost entirely reduced by heat loss through the heat-permeable wall covering the air ducts at the outside, and the temperature of the air current in front of the tray of the westerly air duct is almost the same as the one of open atmosphere.

Then dried air passes the water surface of the tray, and its effect on the vapor is the same as a sponge on liquid water. The vapor pressure of the dried air being low and the pressure of saturated vapor above the water surface being high, the water surface vapor is drawn rapidly into the moving current of air.

Vapor can come into existence only if heat of vaporization is delivered. No other heat source but the enthalpy of the circulating air is present, and the required heat quantity has to be delivered by it. Air can supply heat only by loss in temperature, and the air temperature drops between points A and B of Fig. 2 the more it has been dried. During this time the temperature of the water in the tray is considerably lower than the lowest ambient air temperature. As vapor must be delivered by the quantity of water, its temperature drops to the level sufficient to accept the quantity of heat from the air which is needed to evaporate the extracted vapor quantity.

The cooled air enters the room to be refrigerated in the direction of the drawn arrow. It leaves the room entering the easterly air duct which now has a sucking action, and it passes the easterly absorbent, now in regenerating state.

Regeneration is the more intensive the drier the air entering the regenerator, and the air quantity leaving the cooled room is always of less relative humidity than 100 per cent because it is warmed in passing the room, and no vapor source is present. It would, therefore, accept vapor out of the evaporator on the east side when passing it. To avoid this obvious decrease in regeneration, a separate exit for air is arranged in both side walls. Entrance into and exit out of the refrigerated room is directed by louvers with movable flaps, which open to air pressure in a certain direction, and automatic opening is given for the correct air movement. All further details are given by Fig. 2.

Figures of the obtained refrigeration will be of interest. The procedure can be easily followed in a psychometric diagram. For instance:

(1) Tests run in Liberia, West Africa, prove that at an average atmospheric air temperature of about 85°F between 9 a.m. and 7 p.m. temperature of the moving air current will not exceed about 90°F at point *A*. If at point *A* the relative humidity of the moving air has been reduced to 15, 25, and 35 per cent, point *B* obtains a temperature, respectively, of 62° to 66°F, 67° to 71°F, 72° to 76°F, or the air is cooled without intermediary machinery, respectively, from 19° to 23°F, 14° to 18°F, and 9° to 13°F.

(2) Tests in Cyrenaica, North Africa, Sahara, 150 to 200 miles off-coast, prove that at an air temperature at point *A* of about 85°F, 95°F, and 105°F, and a relative humidity of about 22.5, 17.5, and 12.5 per cent, the air temperature is reduced at point *B* to about, respectively, 64° to 68°F, 69° to 73°F, and 74° to 78°F, or the air is cooled without intermediary machinery respectively from 12 to 21°F, 22 to 26°F, and 27 to 31°F.

This cooling of air to a temperature difference of 10 to 30°F is remarkable. The relative humidity of the cooled rooms rises to approximately 65 to 75 per cent and even during midday hours the attained climates correspond to dry summer in Central Europe. The data show also that the performance of solar refrigeration becomes better the higher the atmospheric temperature, or refrigeration becomes more intensive the more intensive the solar radiation. The drop in temperature is really remarkable, as it is obtained without any mechanically or electrically driven machinery.

SOLAR REFRIGERATION WITH MACHINERY

Described refrigeration without intermediary machinery is the first step in utilizing the new cyclic procedure for lowering temperatures of the surroundings. For machineless refrigeration, the obtained drop in temperature is satisfactory, but it does not yet suffice to refrigerate a cold storage room.

For solving this refrigeration task by directly radiated solar energy, procedures without machinery no longer suffice. However, neither compressor, boiler, nor condenser, etc., as required for every standard refrigeration plant, are necessary. The machinery to be employed is of simpler character. The developed methods are all of one direction: differences in air temperature between saturated and unsaturated air provide the possibility of heat exchange for lowering the air temperature. Within the area between saturated humid air and absolutely dry air a multitude of differences in temperature are possible for heat exchange, and drop of temperature is obtained by the right arrangement of heat exchange. No other additional machinery but ventilators and heat exchangers is required.

Practical development was first handicapped because heat exchange between two air currents presents unfavorable conditions to techniques. The coefficients of heat transfer of air are very small, and these heat exchangers are, therefore, always large and expensive. Moreover, it is a particular attribute of refrigeration technique to move heat quantities by small differences in temperature, thus additionally enlarging the surface of heat exchange.

However, a certain kind of heat exchanger has been perfected to meet the conditions of solar refrigeration. The method in exchanging heat is of special and still unexhausted consequences. For ordinary air it presents an exchange of heat of about 150 to 250 Btu per hour per °F per cu ft occupied by the heat exchanger. The heat exchange rate does not reflect an unreal estimation; it is related to the cleanliness of both the moving air currents. The data are much better than those presented by heat exchange between moving air and evaporating or condensing refrigerant—physically very much better presuppositions. The good heat transmission is obtained with air current of no higher velocity than 3 to 5 ft per sec. The increase in performance is not limited to heat exchange in solar refrigerators. Other techniques will also use the new method in heat exchange, and manufacture at moderate price is to be expected.

With these heat exchangers and with ventilators for moving air, solar refrigeration has been developed to produce temperatures of 33° to 35°F. Attaining lower temperatures is to be expected.

Limitations in size of solar coldstores, refrigerated directly by the described reversible cycle, do not exist. A commercial refrigeration plant of 500 cu ft may just as well be built as a big coldstore of 100,000 cu ft content. The only limit is the amount of adequate solar radiation. These solar coldstores can be run with temperatures of at least 40° to 50°F, and they can be used in practice like any other coldstore.

The described refrigeration plants for coldstores are no stopgap. They are at least of the same performance as conventional compressor or absorption refrigeration. Because of lack of adequate solar radiation, coldstores of this type cannot be run in temperate climates.

REFRIGERATION AT TEMPERATURES LOWER THAN 40° TO 50°F

Often it will be necessary to produce temperatures lower than 40° to 50°F. Lower temperatures can also be obtained by solar radiation, and customary absorption refrigerators are usually employed for transforming solar heat into refrigeration. Absorption refrigerators of really good design present a thermal efficiency

$$\eta = \frac{\text{produced refrigeration}}{\text{inserted regeneration heat}}$$

of 70 to 75 per cent. A good boiler makes use of about 85 per cent of the absorbed heat. Then the practical thermal efficiency of this plant amounts to 60 to 65 per cent, or about $\frac{2}{3}$ of the absorbed heat reappears in the form of refrigeration performance. If inert gas has to be used, as is often unavoidable, the efficiency of the gas current has to be taken into account. It will in no case be better than 70 to 75 per cent, as the cleaned inert gas is of less weight than inert gas loaded with refrigerant vapor, and the same influence is present in temperature exchange of inert gas as between dilute and concentrated solutions. Therefore, the practical efficiency of the standard type absorption refrigerator of small total pressure with inert gas is about 42.5 to 47.5 per cent.

A well designed resorption refrigerator of practically adequate temperature exchange is already better. It presents the known thermal efficiency of 100 to 110 per cent and even somewhat more for conventional refrigeration tasks. This efficiency is considerably raised by rational resorption refrigeration. Depending upon the qualities of the employed mixture, rational refrigeration can attain much higher efficiency than 100 to 110 per cent.

The rise depends on the possible number of compound stages. If temperatures and pressure are withstood by the refrigerant and solvent without disintegration, n compound steps may be used, and with n compound steps regeneration heat is reduced to $100/(1 + n)$ per cent.

The chemical stability of the ammonia-water mixture permits only $n = 1$ compound step for rational refrigeration. By it, the required regeneration heat is reduced to 50 per cent of the usual one, and the theoretical efficiency is raised to the value 200 to 220 per cent. The efficiency of the boiler and the inert gas remain, and rational resorption with the ammonia-water mixture supplies practical thermal efficiencies, again with 85 per cent efficiency of the boiler, of 170 to 185 per cent without use of inert gas and 120 to 140 per cent with use of inert gas. These figures surpass 100 per cent and indicate that more refrigeration is gained than regeneration heat is absorbed.

In comparison to conventional absorption refrigeration of the above calculated efficiency, the practical result is that rational refrigeration delivers 2.60 to 3.10 times more performance without the use of inert gas and 2.50 to 3.25 times more performance with the use of inert gas.

These figures show that all the reported pilot absorption refrigeration units with solar heating for temperatures lower than 40° to 50°F are not yet on the right track. They can obtain the same refrigeration performance with 30 to 40 per cent of absorbed solar radiation. It is rational refrigeration that indicates the way for solar refrigeration, wherever direct transformation of solar radiation into cold is not yet possible.

REFERENCES

1. Dannies, J. H., "Die Resorptionskryotherme." *Allgemeine Wärmetechnik*, July 1956: 200.

Solar air-conditioning and solar refrigeration is treated for the first time in public by this paper. For this reason more literature cannot be enumerated.

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